Effect of density fluctuations on lower hybrid ray tracing and q-profile evolution in transport simulations

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To investigate LH wave propagation in tokamaks, it is important to model scattering of lower hybrid waves by density fluctuations inside the plasma in addition to standard ray-tracing because LH wave propagation can be strongly affected by scattering from density fluctuations. The scattering can have a significant effect on the q-profile evolution, which is important in predictive transport modelling, especially for ITB or hybrid plasmas. In this work, a simple technique to include the scattering in the FRTC code [1] is considered. The model can then be used in either interpretive or predictive transport simulations where LH heating is used. This work reports the first studies with the FRTC code coupled to the Weiland transport model [2] in order to take into account the scattering within JETTO transport code [3]. The model is then used for interpretive studies of two LH pulses at JET. In interpretive modelling experimental profiles are used except for the q-profile which is predicted.

Model for density scattering

The scattering from density fluctuations affects the propagation of the wave in the plasma. Therefore this has to be taken into account when modelling lower hybrid (LH) wave propagation and absorption with ray-tracing. For this purpose a simple model has been added to the FRTC ray-tracing code implemented to JETTO.

The fluctuations are taken into account by a random rotation of the wave in the plane perpendicular to the magnetic field. Consequently, the wave vector itself and its parallel component remain constant. The new wave vector is thus given by

$$\vec{\mathbf{n}}' = n_{\parallel}\vec{\mathbf{e}}_{\mathbf{z}} + n_{\perp}\cos\beta\,\vec{\mathbf{e}}_{\mathbf{x}} + n_{\perp}\sin\beta\,\vec{\mathbf{e}}_{\mathbf{y}}\,, \qquad (1)$$

where β is the angle of rotation with a random direction. In the first stage, this angle is obtained as $\beta = K\,\beta_{\max}$, where $K=\pm 1$ is randomly chosen and $\beta_{\max} = A\;2\pi(r/a)^2$, with A being the amplitude, r the radial position of the ray and a the minor radius. The rotation is performed each step the ray is advanced. In the next phase, this model was improved to a more realistic one that is coupled to the Weiland model.

This was done through the scattering angle, which will be calculated from $\beta = K(2D\Delta t)^{1/2}$. Here, the coefficient $K = \pm 1$ is randomly chosen, Δt is the time difference between two advancing steps and the diffusion coefficient D is found as [4,5]

$$D = \frac{\omega_0}{k_\perp}\left\langle\frac{\delta n}{n}\right\rangle^2 \frac{k_n^3}{k_\perp^2}\left(\frac{\omega_{pe}^2}{\omega_0 \Omega_{ce}}\right)^2 . \qquad (2)$$

Here, ω_0 and $k_\perp$ denote the wave angular frequency and perpendicular wave number, Ω_{ce} and ω_{pe} the electron cyclotron and plasma frequencies, $\delta n/n$ the relative density fluctuation level (in a statistical sense), and k_n is the perpendicular wave number of the fluctuations with the highest $\delta n/n$. Both k_n and $\delta n/n$ are obtained from the Weiland transport model [2] applied for the discharges in the JET tokamak.

It should be rather straightforward to get the quantities from the Weiland model. However, this assumes that the different modes do not add up in phase. If the unperturbed impurity fraction is $b = n_z/n_e$ the total electron density perturbation would be

$$\frac{\delta n_e}{n_e} = (1 - bZ)\frac{\delta n_i}{n_i} + bZ\frac{\delta n_z}{n_z}, \qquad (3)$$

where the ion and impurity perturbations can be obtained for each eigenmode j from the Weiland model. The overall saturation amplitude ϕ normalized by T_e/e is also obtained from the Weiland model. On the other hand, the saturation amplitude, is

$$\left|\hat{\phi}_j\right| = \frac{\gamma}{\omega^*}\frac{1}{k_r L_n}, \qquad (4)$$

where γ is the dimensional growth rate, ω^* is the diamagnetic drift frequency, k_r the radial mode number and L_n the density inhomogeneity length. The relative density fluctuation level in Equation (2) would then be obtained with the help of Equations (3) and (4) as

$$\left\langle\frac{\delta n}{n}\right\rangle = \max_j\left\{\left|\frac{\delta n_e}{n_e}\frac{1}{\phi}\right| \times \left|\hat{\phi}_j\right|\right\} \qquad (5)$$

The perpendicular mode number is given by $k_n = 0.316\ \rho_s\ (\mathrm{RAV})^{1/2}$ where $\rho_s = (c_s/\Omega_{ci})$ is the ion gyroradius at the electron temperature and RAV is the ratio of the perpendicular and poloidal wave numbers of the mode averaged over the mode profile.

Simulations with scattering

In this paper two typical LH shots have been chosen. The first one is a full power LH pulse with steady LH power at P_{LH} = 3.3 MW and the second one is a pulse with LH in the preheat phase only. In this case the LH power was between 1.6 and 2.1 MW. The main plasma parameters and the heating schemes are shown in Fig. 1 on the left hand side. The interpretive JETTO simulations for the two shots were performed at the time slices 13.3-13.4 s for the shot 57321 and 3.6-3.7 s for shot 58383. The density fluctuation levels obtained from the Weiland model, as described above, are shown for the two shots on the right-hand side at the end of the simulations. The fluctuation levels in the central plasma are very low and increase towards the edge. Moreover, for the shot 57321, the level is much larger than for the other shot. The wave numbers do not differ much in these two cases.

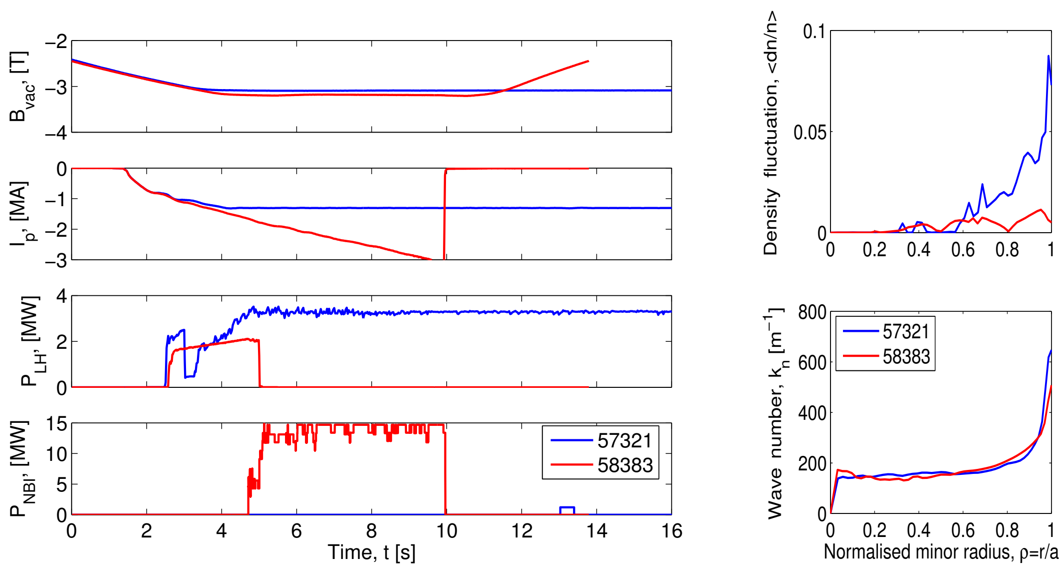

Figure 1: Comparison of the main plasma and heating parameters versus time for the shots 57321 and 58383 from the experiments (left). On the right-hand side a comparison of the density fluctuations and the perpendicular wave number calculated by the model presented in this paper is shown for the same shots at t=3.7 s for shot 58383 and t=13.4 for shots 57321.

The simulation results for the two shots are shown in Fig.2. First the density and temperature profiles are shown. These profiles do not change much during the short simulation nor does the scattering affect these profiles. The lower frames in the figures show the LH driven and the total current densities. For both shots, the scattering from the density fluctuations flattens the LH driven current profile and broadens it inwards. The flattening in especially strong in the shot 57321 where a strong peak is seen at r/a=0.4 in the case without the scattering. This peak vanishes when the scattering is taken into account. The reduction in the LH driven current density peak leads obviously also to the vanishing of this peak in the total current density profile. Consequently, the strange bump in the q-profile seen at this location is smoothed away. In predictive modelling this could have a significant effect on the temperature profile, which would affect the possible ITB. The ITB could move radially or in the worst case even disappear. In the case for the shot 58383, the effect of the scattering is not very strong. It should be noted however, that in this case the density fluctuation level was much lower than for the other shot.

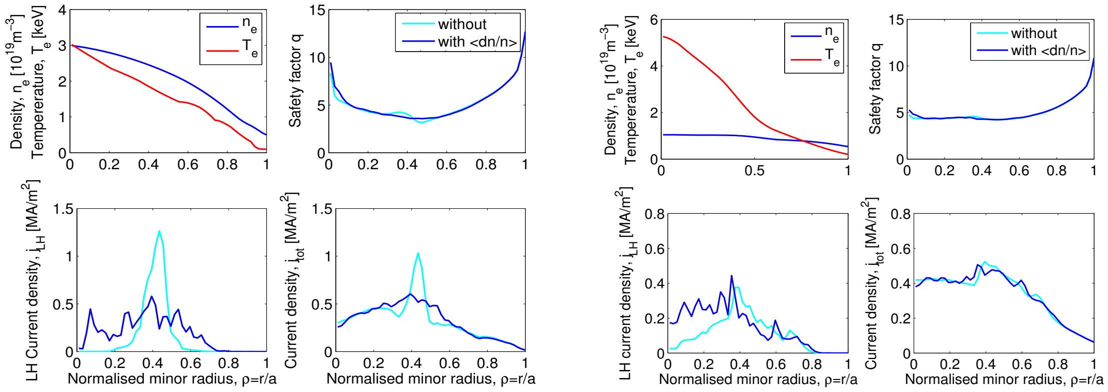

Figure 2: Density and temperature profiles together with the q-profile for the shots 57321 (t=13.4s) on left and 58383 (t=3.7s) on the right. The lower frames show the LH driven current density and the total current density with and without the wave scattering from the density fluctuations.

Summary and discussion

A model taking into account the scattering of the LH waves from the density fluctuations has been included in the fast ray-tracing code FRTC. This model couples the LH model with the Weiland transport model. The density fluctuations are obtained from the transport model and used in the LH model to calculate the scattering angle.

In this first study, this model is used for two JET pulses. It is found that the inclusion of the effect of density fluctuation on the LH ray-tracing provides an important flattening influence on the driven current density profiles. This removes, in an essential way, spurious spikes in j_{LH}, which have been sometimes observed in the ray-tracing calculations, and thus changes the prediction for ITBs and temperature profile evolution in predictive transport modelling.

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